PRESSURE FIELD CHARACTERISTICS OF PARALLEL FLOW OVER A THIN ROD

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RAM JIYAVAN

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TO

GRAND FATHER

CERTIFICATE

This is to certify that the work entitled 'Pressure Field Characteristics of Parallel Flow Over a Thin Rod', has been carried out under our supervision and has not been submitted elsewhere for the award of a degree.

Brajendra Sahay

(K. Sri Ram)
Professor
Nuclear Engg. and Technology
Programme
Indian Institute of Technology
Kanpur

(B. Sahay)
Assistant Professor
Department of Mechanical Engg.
Indian Institute of Technology
Kanpur

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Ram Jivavan

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ABSTRACT

In earlier studies the near-field component of the flow noise has been identified as a primary excitation source in the parallel-flow-induced vibration of flexible rods and tubes. The measurement and characterization of near-field noise is the most difficult part of the vibration problem. In this work an experimental study of the statistical characteristic of pressure fluctuation on the surface of a test element in annular flow at room temperature and atmospheric pressure has been presented. Miniature pressure transducers have been constructed and mounted both longitudinally and circumferentially on the surface of a cylindrical adopter which was flush mounted with the tubular test element. The instrumented test element was concentrically mounted within the test loop. This assembly was used to measure pressure-time history of the near-field flow noise. The auto-correlation coefficients and power-spectral densities were computed from a pressure difference signal using a substraction process, with diametrically opposite transducers, to null out the far-field (acoustic) noise. Spectral variation of pressure fluctuation with flow rates were plotted. The present study shows the feasibility of measuring the excitation function, which is believed to be due to

pressure density fluctuations around the rod. It is hoped that the present results will be used in predicting the response of the vibrating rod in a parallel flow field xx by the well established analytical methods.

CHAPTER I

1.1 Introduction:

Flow induced vibration includes a wide range of vibration problems associated with elastic structures placed in a flowing fluid. Energy needed to activate and sustain these vibrations is derived from the fluid flowing around or through the structure. These vibrations are of self-excited type because it is believed to be initiated and sustained by transient disturbances present in the flow.

In nuclear industry the flow-induced vibration problems are important for optimal design of reactor core which includes closely spaced fuel elements (rods) and in the design of steam generators which contain large number of tubes carrying fluid. Both these problems have been investigated and literatures are available regarding the stability as well as the root mean square (rms) displacements. Vibration problems associated with nuclear power plants such as EBR II [1], GETR [2], Big Rock Point Type BWR [3,4], PWRS [5,6,7] and MSRE [8,9] show that the units have experienced extensive damage due to the flow-induced-vibrations. Generally vibrations in reactors may lead to vibration noise, failure through wear, fatigue and fretting.

A recent paper by Shin and Wambganss [10] reviews the behaviour of steam generators for the LMFBR type of reactors. High velocity flow rates in steam generators using water [11-14] generally leads to failure of the tube bundles which needs frequent replacement. Generally these vibrations are generated and propagated due to far field disturbances and near field disturbances. Typically the pulsating pump flow, vortex shedding in the wake behind the submerged structure, structural noise, cavitation etc. can be classified as far field disturbances. Near field disturbances are mostly the pressure variations around the tube or rod due to the flow around it. Far field disturbance (or noise) generally propagate in the system with the sound velocity, while near field disturbance (or noise) is local in nature and is generated due to the turbulent eddies. Some general observations regarding the flow-induced-vibration effects may be made as follows:

1. Fluctuations in the reactivity of reactor core and hence in the output power level of the reactor.
2. Coalescence of plate type reactor fuel elements [15].
3. Propagation of sound wave of long wave-length through the loops.
4. Secondary vibrations of structural components.
5. Changes in the flow distribution history around the tubes placed inside the heat exchanger-shell.

6. Excessive wear, fatigue and fretting resulting in the breakage of the heat exchanger tubes.

7. Breakage of spacer and end fixtures of rod and tube bundles.

8. Continuous erosion of baffles resulting in baffle-hole enlargement because of hammering and sawing effects of vibrating tubes.

In general the vibrations may be caused by the fluid flow either parallel to the structure axis (parallel flow) or transverse (cross-flow) to the structure axis. Cross-flow problems are important in heat exchangers (steam generators) and in the case of CANDU type reactors, the heavy water dumping in emergency (screan) shut down of the reactor. In general, cross-flow induced vibration is excited by regular vortex shedding in the wake behind the structure, but in case of arrays of parallel tubes or rods, excitation can also arise through turbulent buffeting, fluid elastic whirling, jet switching, propagating açoustic standing waves and hydraulic noise associated with turbulent boundary layer pressure fluctuations. The subject is widely explored and several excitation mechanism have been identified. Empirical and theoretical results have been presented in the literature [14,16-20] and the design guide lines are also available.

1.2 Farfield and Nearfield Noise:

The present study is mostly concerning the parallel flow induced vibrations. Vibration of guide tubes (due to internal flow) and fuel rods (due to external flow) and steam generator tubes (due to internal and external flow) have received wide attention and has been investigated during the past two decades. Parallel-flow-induced excitation consists of nearfield, farfield and structural borne noise. The farfield component comprises all system dependent noise and propagates with the speed of sound in the down-stream. Sources of farfield noise are flow-pulsations, vortex shedding behind the submerged objects, turbulence generated by bends, cavitation etc. In parallel flow there are two components of flow pulsations. One component is longitudinal in which the fluid pressure will vary periodically in the direction of flow. This produces an axial loading over the surface of the element in contact with the fluid. If the up-stream end is fixed, the element experiences varying tensile force and element may vibrate longitudinally. If the fluid is incompressible, this component has negligible effect. The other component is transverse, in which fluid pressure is oscillating in a direction normal to the element axis. It will produce a distributed load over the element and forcing the element to transverse vibration. It may change also the mode of vibration of the element. In both the cases axial flow velocity can be taken as

the mean resultant in axial direction with a randomly varying component.

The near-field noise components are due to pressure fluctuations incurred by the adjacent fluid. The most important near-field noise is the boundary layer turbulence. These pressure fluctuation arise because of locally generated eddies in the turbulent boundary layer. The life time of these eddies are small and depend on their size. Eddy size depend on surface roughness and scale of turbulence. In general, the size of eddies vary randomly. These locally generated eddies start moving in the down-stream and disappear after travelling short distances from their origin. This distance upto which an eddy survives, is dependent on their size and hence is also random. Distance travelled by an eddy in a unit time is known as convection-velocity. One can say that pressure field associated with these eddies will be convected in the down-stream with the speed of convection velocity. The maximum average distance travelled by eddies (hence pressure field) is known as correlation length. The loading on the element, because of near field noise, is randomly varying. Since the generation and disappearance of these eddies in the boundary layer are completely random, the treatment of the problem associated with near-field excitation must be based on random vibration theory. The

generated pressure distribution can be evaluated from the spectral density measurements.

Most of the existing literature on parallel flow induced vibration problem can be classified into two broad categories of stability analysis and response measurements. Stability analysis yields the critical frequencies as a function of system parameters such as flow rates, stiffness, relative rod dimension and flow passages etc. Response measurements generally deal with either direct measurements of displacements or measurement and characterization of field noise which yields the forcing function required for stability and response determination. A brief literature survey of the stability analysis and response measurements is given below.

1.3 Survey of Stability Analysis:

Parallel-flow-induced-vibration problem was first observed in 1885 by Brillouin. Bourrieres [21] has examined the oscillatory instabilities of cantilever pipe (conveying fluids) both theoretically and experimentally. Interest in the subject was reactivated in 1950 by Ashley and Haviland[23]. They proposed wave like solution to the equation of motion and studied the effect of flow on wave propagation and damping. Their result indicates that damping increases rapidly with the flow rate. After their work, a number of

investigators [23-25] reported the instability of cantilever pipes conveying fluids. These authors have done stability analysis and showed that buckling (divergence) type instability can occur at sufficiently high velocities. The instability criteria of thick pipes conveying fluids with different end conditions and flow rates have been also reported [25-34]. It has been shown that oscillatory (flutter) instability may also occur under appropriate conditions. Paidoussis [35] showed that vertical continuous flexible pipes conveying fluid can never be subjected to buckling type of instability. This paradox was confirmed by Paidousis [36] and Thurman et al [37]. They have done nonlinear analysis of simply supported pipe using perturbation techniques, which is applicable only to high velocities. The stability criteria of thin elastic pipes conveying fluid is also reported in the literature [38-40]. The equation of motion was established using shell theory and potential flow theory. It was shown experimentally that instability in the shell is of coupled-mode flutter type.

All the above references deal with stability of pipes conveying steady flowing fluids. Stability analysis of pipes under pulsating fluid flows was done by Chen [41-44], Bohn and Hermann [45]. They supposed that the velocity field consists of a steady component superposed with a harmonically varying component. These studies have been done for simply

supported, straight and curved pipes. They have also included effects of end support conditions, coriolis force and in-plane and out-of-plane motions. Their studies covered free, forced and parametric excitations. They showed that the effect of fluid pressure and velocity on natural frequency are almost similar to that found in steady flow and when the flow is increased beyond the critical velocity (onset of instability) the system returns to stability. Paidoussis and Issid [34] corrected the equation of Chen for stream-wise local acceleration of the unsteady component. The existence of these oscillatory instabilities in case of pinned-pinned and clamped-clamped pipes was explained as the consequence of coriolis force. After the onset of buckling this force stabilizes the system prior to the onset of coupled mode flutter. Again, viscoelastic damping and hysteretic dissipation destabilize the system, but the effect of hysteretic dissipation is not as severe as that of viscoelastic.

Chen [40] extended the work and studied the vibration of a group of circular cylinders. He has considered the effect of adjacent vibrating rods to each other and set a system of coupled differential equation. This is a general method which can be equally applied to cylinders having different properties and to in-plane or out-of-plane vibrations. He showed that lowest frequency of the coupled modes is associated with the in-plane mode motion. He further showed

that fundamental frequency of a group of identical cylinders is inversely proportional to the number of cylinders and spacing between them. As spacing between the cylinders decreases, the coupled frequencies are spread out over a wider range leading to a broad band.

1.4 Survey of Response Measurements:

(A) Direct Measurements:

In 1955 Long [46] measured the free transverse vibration response of a single-span-tube of the cantilever type conveying fluid using strain gauges. It was shown that the amplitude is directly proportional to the flow velocity and also that the forced motion of the cantilever tube was dampened by internal flow. However these experiments did not receive attention till 1958 when Burgreen et al [47] performed the vibration studies of cylinderical rods in axial flow, similar to nuclear fuel elements and steam generator components. Both single rod and rod bundle behaviour were investigated by resistance strain gauges mounted on diamotrically opposite sites of the rod. For rod of $\frac{1}{2}$" diameter placed in a tube of 4 in. diameter, Burgreen et al observed that the vibration frequency was relatively constant over wide range of flow rates, and hence they inferred that the vibrations were of self excited type. In their analysis they assumed that the forcing function was proportional to the dynamic pressure for

fully developed boundary layer. Quinn [48,49] experimentally measured rod vibrations in water at 21 to 61°C and water-steam two-phase mixture at 285°C using strain gauges. The single phase experiments were made to systematically study the effect of velocity, fluid density, hydraulic diameter, mass and the flexural rigidity of the rod. The two phase studies showed maximum vibration response at 7% voids. His analysis includes a centrifugal term to account for the flow acceleration on a bowed rod.

Sogreah [50] experiments were performed in smooth rods in laminar flows, and their results indicate that the surface roughness increases the rod amplitude for actual heat exchanger tube response in water, water and steam mixtures both at room temperature and at 220°C were measured by Rostrom and Anderson [51,52,53]. These experiments also resulted in maximum vibration response at 7.5% void as in the case of Quinn's experiments, furthermore it was observed that the amplitude increased with increasing temperature and velocity. The r.m.s. response of an isolated tube was different from a tube in a bundle. Strain gauges were used to investigate fuel rod bundles at 21 to 65°C by Pawlica and Marshall [54] and finned tubes with hinged and fixed end conditions in the temperature range of 15-18°C by Basile et al [55].

Paidoussis [56] developed a theory for self-sustained oscillations taking the centrifugal force term as suggested by Quinn and velocity dependent drag force. This drag force acts on a body across which fluid is flowing. The results were used to derive an empirical correlation [57] which was an improvement over Burgreen's correlation. The effect of two-phase flow is considered by using effective two-phase density. He has verified his correlation with experiments. It gave reasonable agreement with empirical formulae for a single rod but poor agreement for tube bundles.

Andrews et al [58] measured the mid-span vibrations of a cylindrical rod by optical transducers. Their results showed that only the fundamental mode was excited. The r.m.s. response predicted by using the randomly varying wall-pressure correlation was found to agree well with measured r.m.s. response. Their r.m.s. response was about 4 to 15 times less than the maximum amplitude predicted by Paidoussis correlation, but is in good agreement with r.m.s. response predicted by Reavis's correlation.

In a subsequent theoretical work, Reavis [59] adopted a theoretical model where the rod was driven by a randomly time varying force resulting from turbulence in the fluid. His equation of motion contains elastic, viscous damping, inertia and inertial force exerted by fluid displaced by the

rod. Implimentation of this theory requires various statistical properties of the random two dimensional pressure field that surrounds the rod. Since such information was not available for geometries and fluids of interest, he used the existing nondimensional data, for air-flow through pipes, to calculate amplitude of vibration. He found that the predicted amplitude obtained in this manner was, in general, much smaller than those reported by other experimenters. This discrepancy led to a constant scalar ratio between the theoretical and experimental values for any particular test loop.

Thus it becomes important that the knowledge of the driving force of randomly varying pressure fluctuations is essential in arriving at an accurate correlation to predict the response and stability.

(B) Measurements of Pressure Fluctuations:

The fundamental paper on flow noise has been published by Lighthill [60], who studied the radiation field outside a finite region of homogeneous turbulence. The basic work on the noise pressure within an infinite region of turbulence was done by Kraichman [61] and many of the results arrived in this paper was already contained in his analytical formula. Phillips [62] did some valuable work on the noise pressure radiated by a turbulent boundary layer to greater distances.

Lyon [63] developed an analytical method to analyse the one-dimensional transverse vibration of strings to an axial random load. Dyar [64] extended the method of Lyon to analyze the response of a two dimensional phate subjected to a random pressure field. Skudrzyk [65], presents a first attempt to predict the boundary-layer noise levels and the noise produced by the surface roughness, on the basis of measurements in the boundary layer of the test section of Garfield-Tomas Water Tunnel. This, also, was the first attempt to analyze small scale boundary layer turbulence by means of flow noise studies. Two buoyant units each carrying six hydrophones were used, for data recording on a seven channel tape recorder. Measurements have been done in a wide frequency range. The spectral level of the flow noise was found to increase by increasing flow velocity. They have showed that flow noise produced by the rough surfaces is 20 to 50 times greater than that produced by smooth and polished surfaces. The effect of finite size of the hydrophones was systematically investigated. Kraichman [66] has measured pressure fluctuation over a flat plate, using small microphones, placed in turbulent air flow. He has plotted longitudinal and lateral cross-correlations and spectral density function for different Mach numbers. Cross-correlation curves were approximated by exponential functions. These results were used in deriving a mathematical model for

driving force. Experimental results of smooth and rough surfaces led him to conclude that vibrations are excited not only by pressure fluctuations, but also by shear fluctuations at the surface. The relative contributions of these two type of forces can be estimated only if the degree of coupling of the various modes of vibrations are known.

Tack et al [67] measured pressure correlation over a plate of rectangular cross-section placed in a wind-tunnel. Instantaneous fluctuations in pressures were measured by small microphones. Space time correlation were measured by moving microphones over discrete steps. The eddy drift velocity was determined from the knowledge of the separation distance and delay time necessary to obtain a correlation maxima. They have derived mean eddy drift velocity, for higher band frequency, and found about 0.78 to 0.8 times the free stream velocity. This is in good agreement with the value given by Willmarth [68]. A correlation for the self noise of the sensing device was obtained by extrapolating the cross-correlation pressure response peaks to zero separation-distance. This value was then compared with results obtained by auto-correlation of the response of a single transducer. The excess r.m.s. pressure measured by auto-correlation was attributed to self noise of the transducers.

Measurements of the turbulent pressure field at the wall beneath a 5 in. thick turbulent boundary layer produced by natural transition on a smooth surface was reported by Willmarth and Woolddridge [68]. The data includes mean-square pressure, power-spectrum of the pressure, space-time-correlation of the pressure parallel to the stream and longitudinal, lateral cross-correlations of the pressure. The r.m.s. wall pressure was found to be 2.19 (revised to 2.64 [69]) times the shear stress. The power spectra of the pressure were plotted in terms of reduced frequency (strouhal number). A few tests with rough surface showed increase in r.m.s. wall pressure.

The space-time correlation measurements, parallel to the stream direction gives convection velocity 0.56 to 0.83 times the free stream velocity. Higher convection-speeds are observed when the spatial separation of the pressure transducers is increased or when only low frequencies are correlated. This result is in good agreement with the measurements of Corcos [70] in fully turbulent tube flow. Analysis of these measurements also shows that both large and small-scale, pressure producing eddies, decay after travelling a distance proportional to their scale. More precisely, a pressure-producing eddy of large or small wave length λ decays and vanishes after travelling a distance of approximately 6λ.

The effect of pressure gradient on the spectral properties of wall pressure fluctuations was studied by Schloemer [71]. He has measured turbulent-boundary-layer-wall-pressure fluctuations using miniature transducers in an air tunnel. Spectral properties were measured in both adverse and favorable^{+} pressure gradients^{++} pressure gradients in a low turbulence subsonic wind tunnel. To stablish a basis of comparison, similar measurements were made for the zero pressure gradient. Low frequency content in the spectral density, was found to increase in adverse pressure gradient and decrease in favorable pressure gradient. Convection velocity, decay rate of an eddy was found to be higher in adverse than in favorable pressure gradient. No significant difference was found in the lateral cross-spectral density.

Corcos [72] discussed the measurement of statistical properties of pressure field at the wall in shear flows. He discussed the effect of transducer sizes on the spectral properties and the resolution of pressure field. He showed that measurements of longitudinal and lateral cross-spectral density lead to definition of similarity variables. The existence of these similarity variable (one is along the flow and other is perpendicular to the flow) was assumed due to

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+ Adverse-pressure decreases in the direction of flow.

... direction of flow.

the dispersion of the sources of pressure (eddy) by the mean velocity gradient. This mechanism was illustrated by a simple model which is known as phenomenological model. This model defines the cross-spectral-density in terms of power-density and similarity variables which characterizes the convecting, random pressure field associated with the near-field.

The power spectra of the wall pressure was measured by a transducer of a very small size and correction to the power spectra, measured by finite-size transducers was determined by Willmarth and Roos [73]. They have used four transducers of different diameters. The r.m.s. wall pressure measured by a transducer of a very small size was found to be 2.66 times the wall shear-stress. They showed experimentally that similarity variables introduced by Corcos [72] is not valid for small spatial separation. The range of validity of the similarity was determined by them. They have made transducers of two ceramic materials -- Barium-Titanate and Lead-Zirconate. They have found that Barium-Titanate transducers are less sensitive than Lead-Zirconate (PZT-5).

Backwell [74,75] measured longitudinal space-time correlation function of the fluctuating pressure in a 3.5 in. pipe, in turbulent air flow. He has used 1/16 in. dia

Lead-Zirconate disk and 1/8 in. dia standard sensors mounted flush with inside wall of the pipe. Acoustic filters were used to minimize noise. His results were compared with the theoretical model developed by Corcos [72]. It was found that the maximum space time correlation can be approximated by an exponential. The data was analysed with a fixed band-width of 30 Hz as well as using half octave and full octave band-widths. In all the cases it was found that the agreement between theory and experiment is better for the narrow band case.

Backwell [76] measured the statistical properties of the fluctuating pressure at the wall in the turbulent boundary layer of a body of revolution in a water medium using flush-mounted hydrophones. The non-dimensionalized-spectral-correlation data was found to be in good agreement with zero pressure gradient data on flat plate and with nearly zero pressure gradient data in fully developed turbulent pipe flow. Peripheral correlations were also obtained by mounting hydrophones at 26.5° and 40° orientation from its normal position. These data confirmed the Corcos [72] assumption that the magnitude of the general cross-spectral density function is closely represented by the product of the magnitudes of the streamwise and lateral cross-spectral density functions. He showed that non-dimensional convection velocity depends exponentially on the non-dimensional

frequency. His longitudinal and lateral cross-spectral density can be approximated by exponential curves and was in good agreement with experiments of Willmarth et al [68].

Clinch [77] measured the wall pressure field at the surface of a smooth-walled pipe carrying turbulent water flow. He has designed an assembly of miniature transducers for this purpose. This assembly has 19 transducers fixed longitudinally and peripherally to the assembly. The assembly was ground so that its diameter coincides with the inner-diameter of the pipe. Thin gold foils (0.01'') were used as charge collecting electrodes. The measured longitudinal and peripheral spatial cross-correlations were found to be in good agreement with the results of Backwell [75]. Cross-spectral density was estimated in narrow frequency bands. He found that Corcos [72] analytical model is a good approximation for-cross-spectral density function. Space-time correlation measurements in broad frequency bands shows that convection velocity is a function of frequency and is about 0.76 to 0.81 times the free stream velocity.

Gorman [78] initiated the measurement of spectral properties over the rod surface in annular fluid flow. He mounted a rod in a test section of the flow channel. Assuming same pressure field over the rod surface and at the inner surface of the test section wall, he measured the pressure-time history using standard transducers flush mounted with

the inner surface of the test-section wall. Values of longitudinal and peripheral cross-correlations were obtained for a fixed central frequency of 50 Hz, for different values of transducer separations (angular and longitudinal) and for different liquid velocity. Damping coefficient and r.m.s. displacements were measured by a pair of resistance strain gauges mounted on the surface of the rod. Spatial cross-correlation coefficient curves were approximated by exponential (peripheral) and cosine functions (longitudinal). R.m.s. amplitudes were obtained using linear random vibration theory.

Wambsganss and Zaleski [79] was first to identify and characterise the near field excitation acting on the surface of a smooth flexible rod placed in parallel-annular flow. They constructed three longitudinally in-line pairs of miniature pressure transducers on diametrically-opposite surfaces of the rod. Barium-Titanate crystals were used in constructing the transducers. Each transducer was mounted on strain relief pads to avoid strain sensitivity. These transducer pairs were placed 0.1" and 0.2" apart. Transducers were calibrated in a small circular section having same conditions as in the test section, for frequency response. This instrumented test element was then used for pressure-time history measurements. The correlation plots are some what different than previous results for plate [68].

Gorman [80] conducted a series of tests in which a single test element has been subjected to two-phase (air + water) parallel flow in an annulus. He has used the same set up described in [78]. He showed that a high peripheral correlation of the driving forces are responsible for the large vibrations. But the spectral data of driving forces was not in agreement with the other experiments. Longitudinal cross-correlation coefficient curve was approximated by exponentially damped cosine function and peripheral correlation coefficient by a resultant of cosine and a sine functions.

Harris and Holland [81, 82] have measured vibration amplitude of a cantilever rod in two phase (air-water) parallel flow by direct and by pressure fluctuation measurements. Vibrational amplitudes were measured by two pair of semiconductor strain gauges and pressure statistics, near the free end, by a pair of pressure transducers mounted near the free end, on the wall of the test section. R.M.S. pressures were measured for different end shapes and maximum value was obtained for stream-lined shape. Analytical result showed that amplitude, damping and resonance frequency of the rod are increased with increasing void and will be maximum at 7% void, This result was verified by experiment. They found that differential wall pressure correlation coefficient and dynamic strain are exponentially

Winsbury and Ledwidge [83] has measured vibration-amplitude in two-phase flow, of a thin tube in a 7 tube cluster representing part of a nuclear fuel element, with electrical strain gauges fitted inside the tube wall at different flow rates. They predicted an empirical relation for maximum amplitude, based on experimental data, in terms of volumetric flow rate. Recently, Gorman [84] studied the vibration behaviour of the central rod of a seven rod bundle simulating BWR reactor fuel pin. The central rod was kept at simply-supported end conditions and other six rods were fixed. Amplitudes were recorded by two pairs of semiconductor strain-gauges and pressure fluctuations were measured by pressure taps for different void and flow rates. He found that above 16% void, amplitude of oscillation is independent of flow-speed and void-fraction. Also, the measured amplitude of a pin in a bundle is higher than same pin in isolated case. Gorman and Mirza [85] adopted a new technique to measure the local driving force over a rod immersed in a fluid flowing through a channel parallel to the common axis of the rod and channel. Their sensor was a thin zircolloy tube of outer dia same as test rod and length equal to the half the rod length. A pair of semiconductor strain gauges were mounted on diametrically

opposite inner surfaces of the tube. Half portion of the rod was ground to fit the tube over it. Tube was a cantilever because of the clamping at its upstream end. A small clearance was left for tube vibration. Signals give the stresses normal to the tube surface. An expression for the driving force was given in terms of system parameters.

Survey of the above literature shows a remarkable development towards parallel-flow-induced-vibration problem through stability and response analysis. It further appears that the dynamics of pipes transporting fluid (internal flow) and tubes/rods located in the stream of flowing fluid (external flow) were developed more or less independently. The problem of external and internal flows differ mostly due to bouyancy and added frictional forces. All the earlier response measurements adopted either deterministic (direct measurement) approach or probabilistic (forcing function) approach. The first group has forgotten the solution of equation of motion and predicted empirical relation for maximum amplitude.

The second group offer an alternative approach to the problem postulating the vibration as excited by randomly fluctuating pressure field. Many aspects of the pressure field (forcing function) are still unknown because of lack of experimental data. Accordingly the present work was carried out to fill the gap.

1.4 Present Work:

A survey of the above literature motivated to collect more information about dynamic, convecting random pressure field around the tube/rod in annular flow. Accordingly axial and peripheral fluctuating differential pressure-time history, over the tube surface, was measured by miniature pressure transducers fabricated in our laboratory. Various correlation functions and density spectra are presented in the present work. Miniature pressure transducers were constructed, in Nuclear Engineering Lab. (NE Lab.) using ceramic bimorph crystals. These transducers were mounted to the assembly to get flush mount with the tube surface. Two such assemblies were mounted on diametrically opposite faces of the tube. Coaxial-low noise cables were taken out through the tube as electrical lead from the sensors. These transducers were calibrated for static pressure. Instrumented tube was mounted in a test-section delivering water at room temperature and at atmospheric pressure. Interface electronic equipments were all designed and fabricated. The experimental environment was very noisy, so a lot of care was taken during design and fabrication of transducers and electronic equipments. Initial signal was amplified, filtered and then fed to analog to digital convertor (ADC) of IBM 1800 using on line

facility available at IIT Kanpur. The digitized data has been recorded on a magnetic tape. Data analysis and plotting of results has been carried out on IBM 1800.

Chapter II of the thesis contains brief description of physical layout of the system (hardware), functions of the various parts of the test-loop, method of transducer construction and their calibration, electronic equipment design, fabrication and testing and the data recording system. Chapter III describes the analysis and results of the data. Chapter IV describes the results, discussion, conclusions and some useful recommendations for future work.

CHAPTER II

EXPERIMENTAL SET-UP AND SIGNAL CONDITIONING

2.1 System Description:

The schematic view of the experimental set-up is shown in Figure 1. The test loop consists of several removable sections and is an open loop system. It consists of cast iron pipes with 15.5 cm inside diameter and 3 mm thickness. The horizontal test section can accommodate upto 2 meters long test element. A centrifugal pump (22 H.P., 1460 rpm) delivers water into the flow loop at flow velocities upto 15 meters per second. A surge tank, kept at about 9 meter height, is connected with the loop by a 20 cm internal dia pipe to feed water into the loop under gravity. Flow through the loop can be controlled by two inlets and one outlet valves (v_1, v_2, v_3). Outlet water is collected in a flow rate measuring tank. This water is taken back into the storage tank through a cement sewer.

The loop has been designed with minimum bends, valves and reducers to minimise far-field (system dependent) noise. The loop is fitted with one vibration isolator (IV), two flow straightners (FS1, FS2), five sets of acoustical

filters (AFT, F1-F4), one test section, one pair of acoustic transducers (AT) and 16 transducer mounts (T_1, T_{16}), A 50 cm. Perspex pipe (TP) is introduced into the loop, before the test section, to observe the flow in the loop. Inlet water can be controlled by a main control-value and a sub-way value which is used for fine adjustments of the flow. Pump foundation vibration was minimised using sand damper technique. To supress the transmission of residual foundation vibrations through the structure, a flexible rubber section is used as vibration isolator. Details of the components used in the loop is described below.

2.2 Component of the Set-up:

The experimental set-up consists of the following components:

a) Flow straightner

b) Acoustic filters

c) Test section

d) Test element

e) High pressure section

a) Flow Straightner:

In order to regulate the flow field, two flow straightners FS1 and FS2 are installed into the flow loop Fig. 1. FS1 is a small (20 cm long) straightner made of layered steel sheets. It is mounted just after the cement

tank acoustic filter AFT. The irregularities coming from the AFT will be minimised by this straightner. The mechanism is similar to the wave regulating mechanism in the radar system. In the region of the straightner square/circular flow field coming from the AFT will be divided into thin rectangular layers and will die out while passing through it. FS2 is mounted between the acoustic filters F1 and F2. It is a one meter long pipe section, tightly fitted with thin wall, aluminium tubes. The axis of each tube is supposed to be parallel to the loop axis. Because of the long narrow path, inlet radial irregularities in the flow will be reduced in the outlet flow.

b) Acoustic Filters:

Far-field transverse noise is minimised by 5 sets of acoustical filters. One of these, is a cement tank AFT placed just after the rubber section RS and out of the other four, 2 sets are installed on each side of the test section. In the flow, transverse and longitudinal irregularities are present. These far-field noise originate from pump pulsations, bends, cavities etc. Cement tank AFT is a rectangular (30 x 30 x 16 cm) concrete tank. It acts as a single stage filter. The loop pipes are cemented to its upper and side faces, so that flow turns at 90° from its original path. Since the diameter of the pipe is 15.5 cm, hence the maximum

wave length of the propagating circular wave is 7.5 cm. (half of the radius). In order to get maximum cut off, frequency, height to width ratio of the tank should be 1:4. Accordingly required tank width is 30 cm and calculated cut-off frequency of the tank is 20 KHz. This filter reduces the far-field noise by the following mechanism:

1) Change of material in the flow path produces damping to the structural noise.

2) Change in wave shape reduces the noise level. Far-field flow noise propagating in the form of circular waves will become rectangular in the tank and since the tank outlet is a circular pipe having layered flow straightner FS1, the incoming noise will be reduced.

3) Reflection produces absorption of the wave. Flow field gets a 90^{o} turn when passing through the cement tank. Because the tank material is some what porous, some of the sound wave will get absorbed by the material.

Another set of filters F1 and F2 were installed in the loop to attenuate the extraneous low-frequency far-field noise. Each set of these filters consists of three circular pipes of the same specifications as loop pipes and of 1 meters average length. The actual length of each pipe is different from each other. These pipes are connected to the loop by short T sections, located at the bottom of each

pipe. One set of these filters is installed in the upstream and the other in the down-stream. Each circular pipe of these filters has large opening area and acts as a resonance column. These pipe columns are mounted vertically on the horizontal flow-loop. During operation these pipes are filled with air at room temperature using an air compressor. To adjust the water level (i.e air pressure) in these pipes, air leak-control system and controlled air-feed systems are provided. These pipes act as high pass filter. The calculated cut-off frequency of these two sets of filters is around 375 ± 50 Hz. These filter stages will attenuate the low-frequency far-field noise level to reduce the 'masking' problem caused by the noise.

Further reduction of far-field noise was achieved by introducing two more sets of acoustical filters (F2, F3). Each set was installed on either side of the test section and in between the filters F1 and F4. These filters are similar to those used by Paidoussis [57] and Wambsganss et al [79]. Each filter system consists of three rubber tubes of large diameter. Each rubber tube connected with the flow channel by short pipes of 7.5 cm internal diameter. These pipes are welded with the flow loop, pipings such that the axis of these small pipes are vertical. Because of small diameter (7.5 cm) the cross-sectional area of the pipe

to volume ratio of rubber tube filters is very small and hence act as semi-infinite cavities. These rubber tubes are fitted with air and are connected with air compressor during operation. These filters also act as high pass filters. Cut off frequency of each rubber tube filter is about 100 Hz. These filters are quite effective. The test section is installed between the filters F1, F2 and F3, F4, to isolate it from inlet and outlet acoustic noise sources. The over all effect of these filters is believed to be sufficient to attenuate all the far-field noise to a minimum whose effect can be neglected in the present vibration study. The residual low frequency far-field noise can be measured with a pair of acoustical transducers,AT, mounted diamatrically opposite.

c) Test Section:

Test section TS is a 2 meters long 15.5 cm internal diameter mild steel pipe, placed between the filters F2 and F3. Two end plates are bolted on each side of the test-section. These end plates are aluminium flanges having steel supports of aero-foil section, which can be adjusted in and out to a very minute amount (0.01 mm) to support the test element in the centre of the test section. Test section is made to accommodate 2 meters long test element to avoid the effect of a small inclination of test element from the

test section axis. Test section has five pairs of transducers mounts in the middle region. Each pair of these mounts are welded to the test section pipe on diametrically opposite sides. A pair of standard pressure transducers can be mounted in each of the diametrically opposite mounts of a pair to measure pressure fluctuations history of flow at the wall of the test section. Variation behaviour at different hydraulic diameter can be studied by using either test sections of different internal diameter with reducers/expanders or test elements of different outer diameter. Two test sections and four test elements are available to study the hydraulic diameter effects. In the present work, spectral properties of the fluctuating pressure was studied for only one hydraulic diameter (13 cm).

d) Test Elements:

Four single span cylinders of different diameters are available to use as test elements. The length of each test element is about 3.0 meters. A larger length was chosen so that each end of the elements can be fitted with conical plugs to reduce the disturbances produced due to flow separation at the ends. Each element has 8 pairs of small holes as shown in Fig. 2. Eight holes are distributed to give five axial points and four circumferencial points on the surface of the test element. Miniature

pressure transducers are mounted in each of the holes to get pressure time history at the element surface. Instrumentation of these transducers is a difficult task. In the present study, only one element, which is a 2.5 cm aluminium tube, was instrumented. Instrumentation technique of the element is different from the techniques adopted by Clinch [77,86] and Wambsganss et al [79]. Two identical holders have been used, each instrumented with 8 transducers at identical points. Holders are fitted into diametrically opposite slots, in the middle region of the element. Transducers are mounted over the holder surface to get flush mounting with the test element. To achieve flush mounting, holders were ground in the form of semi-circular rods of diameter equal to the outer dia of the element and sides of these holders were milled to fit into the slot. Finally both the holders are bolted with the element. Electrical leads of coaxial low noise cables, are taken out of the tube from the down stream end.

c) High Pressure Section:

Down-stream filter stages, F4, can be separate out from the rest of the loop to use as a high pressure section. This facility makes the set-up to work as a circular shock tube which can be used to calibrate the constructed miniature pressure transducers by shock tube analysis.

2.3 Instrumentation and Signal Conditioning:

a) Transducer Fabrication:

Corcos [72] and Wambsganss et al [79] showed that the characterization of the cross-spectral density i.e. near-field noise, requires knowledge of power spectral density and the narrow-band longitudinal and peripheral space-time correlations. These spectral properties can be obtained by measuring dynamic differential pressure - time histories at closely-spaced points along the axis and around the middle point of the element. To make these measurements, miniature pressure transducers are needed [87,88]. To get better resolution and high frequency measurements, relatively small size transducers are necessary, since large size transducers averages the high frequency signals. Small size is also required to get small transducer spacings to compute correlation (decay) length, mean life time and other relevent properties of the pressure field.

Sufficiently small transducers are not available commercially and since Clinch [86] and Wambsganss et al [79] showed the feasibility of constructing these miniature transducers, it was decided to construct our own transducers at IIT Kanpur from ceramic piezoelectric material.

Requirements and limitations of present study need that the sensors are mounted flush with the surface of the test element and possess,

1. High resolution
2. High pressure sensitivity
3. High stability
4. High output
5. High reliability
6. Feasibility to mount over any test element
7. Small size
8. Low noise
9. Low cost

Some of these properties contradict each other and hence a compromise has to be made in designing the transducer. Accordingly rectangular bimorph disks of (13 x 3 x 0.6) mm was cut into (1.2 x 1.2) mm. square disks to make the transducer. Bimorph disks consist of two thin piezoelectric transducer elements joined together with the faces of same polarity in contact with each other. Bimorph elements are made of a new compound Lead-Zirconate-Titanate (NPL ZT-5), developed by National Physical Laboratory, New Delhi. Bimorph has high dielectric constant (1750 K), high charge sensitivity (3.1×10^{-10} coulombs/Newton), high frequency constant (1900 N), high density (7.5×10^{3} kg/meter^{3}) and low discipation factor (1.5). It possesses sufficiently high

Curie temperature ($320^{o}C$), to be used also for two phase (steam-water) flow studies.

The (13 x 3 x 0.6) mm ceramic bimorph disks were sliced into (1.2 x 1.2) mm square wafers using crystal cutting machine available in the Semi-Conductors Devices Lab., IIT Kanpur. Although, the square shape effectively behaves as large diameter circular disk, they were used because of the relative ease of their availability and cutting problems. In actual usage the effective sensing area is more dependent on the opening surface area of the transducer, rather than the ceramic size. After cutting and polishing, each wafers were cleaned and inspected for chipping and size defects. The sides of each disks were coated with insulating lacquer (Nail Polish) to remove the possibility of partial short circuit on the edges of the ceramic square with the conducting cement used to cement the pieces together. The paint was easily chipped and scraped out to clean the disk surface in the appropriate area for cementing.

Fig. 3, shows a schematic diagram of a miniature pressure transducer assembly. This type of transducers were mounted on two identical aluminium adoptors that could be installed in the diametrically opposite slots milled on the wall of the test element. A pair of screws were used to

seal these adapters with the wall and with each other. Adaptors were made from aluminium rod of 2.5 cm dia. It was bored to get 1.5 cm hole in the rod and then cut along the axis in two identical semi-circular tubes of about 3 cm length. A T-shaped groove was milled in the outer surface of the rods to 2 mm depth and 3 mm width to accommodate the transducers. Eight transducers were mounted in the slots, 5 in the longitudinal direction and 4 on the circumference with one common point. The closest separation between two transducers is 4 mm and the maximum separation is about 3.8 cm in longitudinal direction, and the minimum and maximum angular separation between the circumferential transducers are found to be 10 and 70 degrees respectively.

Because of the small size of each transducer the mounting operation required an illuminated microscope of large magnification. The procedure used during instrumentation of the element is as follows.

1. A pair of holes of 1.5 mm dia was drilled in the adoptor, adjacent to the slot. A teflon sleeve was inserted through each hole for electrical insulation.

2. The adaptor slot was painted with transformer-insulating varnish to avoid electrical contact between transducer and adoptor.

the impedance of the disk combination without affecting the pressure sensitivity. Upper face of the top disk was then attached to the strain relief paid by a gold foil.

9. Two plastic spacers were set across the slot width to form a barrier between the transducers. The area between the transducers were filled with RTV (silicon) rubber mixed with small amount of Araldite.

10. When the RTV rubber has hardened, the plastic spacers were removed and the area surrounding each transducer was filled with RTV rubber.

11. During the transducer mounting and filling the gaps with RTV rubber, care was taken to get smoothness and flush mounting with the adoptor (hence test element) surface.

Fig. 4 shows the completed transducer assembly mounted on the adoptor. Electrical leads from each transducer was taken out through semi-circular slot, milled on the opposite surface of the adopter and cemented with the adopter body. Two identical adopters having identical transducer assembly were constructed. The tubular test element was instrumented by fitting the adopters in the diametrically opposite slots milled in the middle region of the element. The leads were allowed to run through the tube and taken out through a hole, drilled near s support fin on the down stream. This does not disturb the flow field significantly and also the electrical leads are prevented from oscillations.

b) Transducer Calibration:

Transducers can be calibrated by one of the following methods [89]:

1. Shock tube test to check over-all linearity of the response for different shock pressures.

2. Acoustic-cavity test by comparing with a standard transducer or microphone.

3. Transducer response recording by exciting it with electromechanical exciter at known frequencies and at the mean pressure level equal to the operating pressure level of the set-up loop by using pressure chamber.

The mean pressure level can be controlled by servo valve.

4. Transducer output recording for step change in static pressure which gives the static calibration. In the present work the static calibration was carried out. Transducer output was measured for step change in static pressure. For this purpose a pressure chamber was built to operate at various static pressures. This consists of a small cylinder having the same specifications as the test-loop pipes. The cylinder was fitted with pressure-gauge, valves and transducer mounts. One of the end flanges was filled with rubber plugs. The adopter on which the transducers have been mounted is

kept in the calibration chamber. Air compressor was connected to the inlet value of the chamber. The pressure in the chamber was changed in steps. The transducer output was amplified and recorded on a calibrated oscilloscope. A block diagram of the scheme of calibration is shown in Fig. 5. After properly setting the amplifier gain, a plot of transducer output versus chamber pressure was obtained. The over all efficiency of the transducer was found to be approximately 3.2 volts/psi. Legends of the Fig. 5 are given below:

C	Pressure chamber
T	Test element
PT	Pressure Transducer
PG	Pressure Gauge
V_1, V_2	Control Valves
TM	Transducer **Mounts**
CA	Change Amplifier
LA	Linear Amplifier
OS	Oscilloscope
DR	Data Recording equipment

c) <u>Signal Conditioning</u>:

Another essential part of the experiment is signal conditioning. Fig. 6 shows a schematic diagram of the signal conditioning and recording system. To remove the

static or initial DC charges produced in the transducer, each transducer output is fed to an AC coupled charge amplifier (CA). Amplified signals from diametrically opposite transducers ($T_A . T_B$) are fed to differential amplifier (DA). The output of DA is true differential dynamic pressure signal. This signal is fed to a linear amplifier (LA). The amplified differential signal is transmitted, through low noise coaxial transmission line, to the data recording end. Because of attenuation and other noise, signal may pick-up 50 Hz noise. To filter and amplify, the signal is fed to input interface and filter system (IF). The filtered and amplified signal is then fed to the analog to digital converter (ADC) and data recording unit (DR) of the process-computer IBM 1800.

The following electronic equipments are designed and fabricated for the signal conditioning circuit:

1. Linear Amplifier
2. Filter
3. Differential Amplifier

The circuit diagrams of the above units are shown in Figs. 7, 8 and 9.

2.4 IBM 1800 System:

IBM 1800 is a process computer has the following facilities for on line data logging and computation of the signals.

1. Analog to Digital Converter
2. Interrupt facility
3. Process input-output devices
4. Real time clocks.

The process input-out devices enables it to receive/send signals from / to systems. One can directly record signals from sensors like transducers. Its DACS is capable of accepting one or more analog/digital input signal. When more than one signal is to be processed simultaneously a multiplexer scans the signals sequentially. For high speed data acquisition, the solid state multiplexer was used. It accepts signals in the range of $\pm$ 5 volts. The maximum scanning frequency of this multiplexer is 20,000 points per second.

Scanned signal is fed to ADC of IBM 1800 which converts bipolar signals to digital form. The output of the ADC is in the binary form which is stored in the memory and can be transferred to tape with the help of link program. The details regardingx various components and functions of IBM 1800 are given in Reference [90].

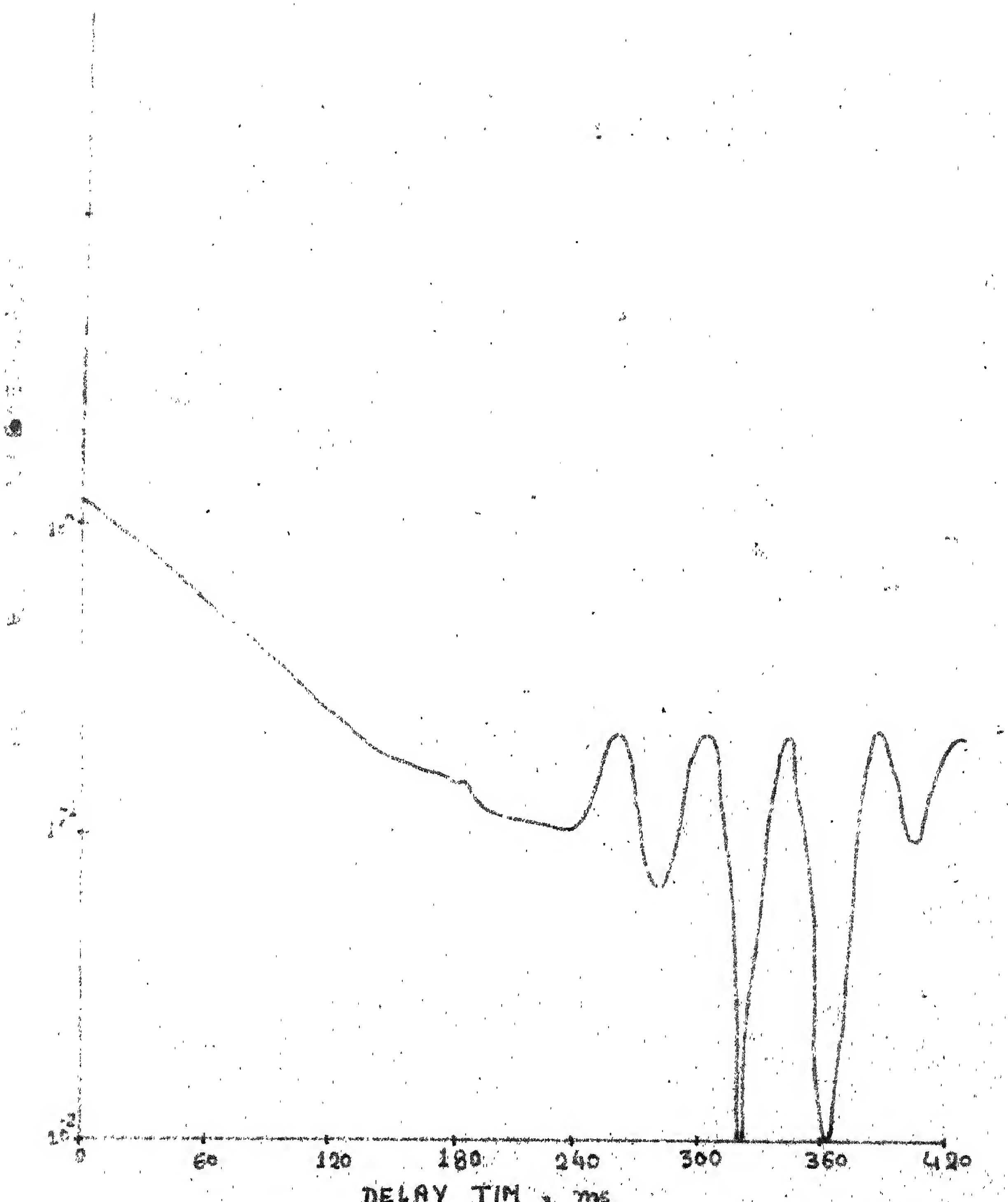

FIG. 10. CORRECTED AUTO-CORRELATION COEFFICIENT

CHAPTER III

RESULTS

3.1 Data Acquisition and Plots:

Near field flow-noises are small scale, random pressure fluctuations producing dynamic load over the rod surface. Correlation technique has been used to determine and characterize these near-field flow-noises. Because of lack of data (available in literature) at low frequencies, in this work measurements have been made only at low frequencies (below 50 Hz). The possible effect of low frequency 'extraneous' (far-field or acoustic) noise has been minimised by taking the pressure difference from diametrically opposite pressure transducer pair as proposed by Wambsganss and Zalesky [79]. In this chapter the auto-correlation functions of the response from longitudinally and circumferentially spaced transducers were computed. During each run of 20 sec. duration the analog signals from the transducers were digitized and stored on a magnetic tape. For each transducer, 300 data points were used in computing the auto-correlation function. The IBM 1800 plots of the auto-correlation indicate that in this manner one complete period of the signal is analysed. The curves have been normalized such that at zero time delay the value of auto-correlation function corresponds to unity.

A digital computer programme for obtaining the spectral density was written for IBM 7044. All the auto-correlation functions were analysed with this programme and the resulting power spectral density (PSD) curves were plotted.

Several general observations have been made regarding the auto-correlation plots. The amplitude of all the correlation functions change their sign, however, the net area of the curve is always positive satisfying the condition of positive-definiteness. The function decreases continuously with increasing delay time and then fluctuates due to limitations of instrumentation and noise effects. The largest negative value of the auto-correlation curve (Fig.11) was added to the computed values of the correlation coefficient so that the coefficients are all positive. This shifted curve is plotted on semi log coordinates as indicated in Fig. 10. It is apparent from the figure that the slope gives the characteristic frequency of 38 Hz as indicated by the peak in the power spectral density (PSD) curve (Fig.16), while the fluctuations at large delay times are mostly due to noise. This shows that, side band effect will be pronounced after a delay time of 200 ms. Since the computed auto-correlation function is dependent on the sensitivity of the particular pressure transducer and the gain used in the amplifiers, no attempt was made to compare the relative behaviour or intensity of these auto-correlation functions.

A general observation of the PSD curves shows decay of PSD value with increasing frequency. A well defined peak is seen at around 38 Hz. This peak in PSD curve is invariant with respect to the location of the transducers or the flow-rate and is almost coincident with the calculated natural frequency of the rod (41 Hz). When the rod is excited at its natural frequency, resulting amplitude is large and disturbance in the flow, produced by the vibrating rod, will also become large. This explains the predominance of the peak near 38 Hz. Other peaks in the PSD curves were observed both below and above the resonance frequency. The small peak at around 50 Hz shows the effectiveness of the filter used to eliminate the 50 Hz electrical noise. The relative areas under the PSD curves below 24 Hz and above 48 Hz seem to vary with flow rates as indicated in Figs. 59 to 61. From these figures one can conclude that the pressure field is redistributed with variation in flow rate.

Fig. 11 to Fig. 15 show the auto-correlation coefficients at the axially distributed points 1,2,3,4 and 5. Points 3,1,2,4 and 5 are spaced at 10, 4, 8 and 16 mm intervals, respectively. Auto-correlation coefficient decreases for the smaller delay times and varies smoothly for larger delay times. Fig. 16 to 20 are the corresponding power-spectral-density functions. These curves show that PSD value is decreasing with frequency. All the curves

exhibit a well defined peak near the natural frequency of 38 Hz. The frequency of the peak is nearly constant at all the points of measurement. The area around the 38 Hz peak varies from 22 to 26 percent of the total area.

Fig. 11 and Figs. 21 to 23 show the auto-correlation functions at circumferentially distributed points 1,6,7 and 8, respectively which are at 0, 10, 30 and 40 degree orientation for 1 m/sec. flow velocity. Figs. 16 and Fig. 24 to 26 show the corresponding power spectral density curves. Again the 38 Hz peak is obtained showing resonance effect. It is not conclusively shown, however, it is suspected that the peak frequencies are varying with the orientation of the transducers except for 38 Hz peak.

Figs. 27 to 31 show auto-correlation coefficients at axially distributed points 1,2,3,4 and 5, respectively at 2 m/sec flow velocity. By comparing with the 1 m/sec. flow rate the peaks at the high frequencies are a little more predominant. Figs. 32 to 36 are the corresponding PSD curves, for this flow velocity, showing decay of PSD values with frequency. 38 Hz peak is again predominant.

Fig. 27 and Figs. 37 to 39 show the auto-correlation functions at circumferentially distributed points 1,6,7 and 8 at the 2 m/sec flow rate. The corresponding PSD curves are shown in Fig. 32 and Figs. 40 to 42. PSD curves again show peak at 38 Hz along with other low amplitude peaks.

Figs. 43 to 47 are the auto-correlation coefficient plots at 4 m/sec flow velocity, for the longitudinal points 1 to 5, respectively. Figs. 48 to 52 show the corresponding PSD curves. Fig. 43 and Figs. 53 to 55 are the auto-correlation coefficient curves at peripheral points 1,6,7 and 8, respectively. Fig.48 and Figs. 56 to 58 are the corresponding PSD curves.

Fig. 60 indicates that the area around the 38 Hz resonant peak is about 22 to 26 percent of the total area. Also it shows a linear dependence on the flow velocity. Fig. 59 shows that the area under the PSD curve below 24 Hz is decreasing with flow velocity indicating excitation of higher frequency models due to increase in the driving function. Fig. 61 shows that the area above 48 Hz and below 72 Hz is increasing correspondingly.

Cross-correlations could not be computed due to the non-availability of IBM 1800 for on-line processing and also attempts to procure multi-channel tape recorder were not successful. The velocities quoted here are from the V-notch measurements.

CHAPTER IV

CONCLUSIONS AND SCOPE FOR FUTURE WORK

4.1 Conclusions:

In general, results obtained from the experimental study and characterization of the wall pressure on the rod surface in annular water flow showed similar behaviour as expected based on published experimental investigations of wall pressure fluctuations in pipe flow and in flow over flat plates. The following specific conclusions may be drawn.

1. The indigeneous construction of reliable miniature pressure transducers, that are sufficiently strain insensitive and possessing inherent flexibility, is possible. The pressure sensitivity can be increased by using bimorph crystal instead of single crystals.

2. Low-frequency 'extraneous' (far field) noise can be effectively eliminated by taking the pressure difference from a diametrically-opposite, pressure transducer pair. This is in resonable agreement with the expected acoustic nature of the far-field. It further shows that acoustical noise is not part of near field noise.

3. Side band (external electrical noise) effects are pronounced only at high delay time (or very low frequencies) indicating that signal conditioning system developed is sufficient to give good results in the frequency region of interest.

4. Narrow-band, low frequency (50 Hz) power spectra is essentially decaying out with increase in flow velocity. Peaks in the PSD curves show the presence of low frequency-large size eddies in the flow field.

5. PSD curve between 48 Hz and 72 Hz increases with increase in the flow velocity indicating the formation of small size eddies of high frequency.

6. As flow rate increases, intensity of the fluctuation will also increase. This result is in good agreement with the expected behaviour, i.e., as the flow rate increases locally generated eddy size increases and thereby gives large intensity and a shift in the frequency spectrum.

7. A plot of correlation coefficient (around 38 Hz) versus flow speed at the centre of rod shows increase in correlation coefficient with increasing flow velocity.

4.2 Suggestions for Future Work:

1. Transducer construction should be done with the help of a high power microscopic.

2. Dynamic calibration of miniature pressure transducers is essential for the study of present problem.

3. Complete characterization of near-field flow-noise, in low frequency region, narrow-band, cross-correlation study is essential. Accordingly data either from all the transducers or at least from two pairs (i.e. from two points) should be simultaneously recorded. So multichannel tape recorder unit should be used.

4. At small flow rate, high rate of data recording should be done to get small delay time as required in cross-correlation analysis.

5. To get better results, signal should be averaged over as long period as possible. This time duration should not be less than one second. It is advisable to average the data for a minute whenever possible.

6. Spectral information of pressure fluctuations at higher flow rates should also be done using the present test rig.

4.3 Plans for Future Work:

1. To study the parallel flow induced vibration problem to near field flow noise, three more test elements are available. These elements have different diameters, so that effect of hydraulic diameter can easily be studied.

2. Study of natural frequency and model damping ratio of the test element for different hydraulic diameters and at different flow velocities should be investigated.

3. This technique of predicting vibration response is relevent to the vibration problem associated with heat exchanger tubes and nuclear fuel elements in a bundle, so that the study of near-field flow noise using 4 and 7 rod bundle should be analysed.

4. The test-section has facility to introduce external pulsations in the flow. It will be interesting to study the above cases under pulsating flow.

5. The spectral data of pressure fluctuations obtained using the test rig is to be used as the forcing function in the analysis and prediction of parallel flow induced vibration of rods and bundles. The mathematical model is already available in the literature.

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